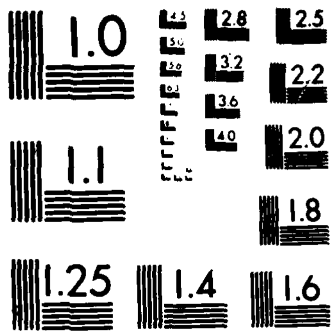
AD-A182 987 FREE-ELECTRON LASER RESEARCH AT THE UNIVERSITY OF CALIFORNIA SANTA BARBARA(U) CALIFORNIA UNIV SANTA BARBARA DEPT OF PHYSICS L R ELIAS 1987 1/1

UNCLASSIFIED N00014-86-K-0692 F/G 9/3 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

(1)

FREE-ELECTRON LASER RESEARCH AT THE UNIVERSITY OF CALIFORNIA, SANTA BARBARA*

Luis R. Elias
Physics Department
University of California
Santa Barbara California, 93106

1987

ABSTRACT

A review of free-electron laser research at UCSB is presented here. Among the topics included are: 1) the development of high-quality electron beam sources based on electrostatic accelerating fields, 2) the analysis of present FEL operating characteristics, 3) the development of advanced FEL concepts, and 5) the utilization of the UCSB FEL in scientific research.

* Work supported by the Office of Naval Research under contract N00014-86-K-0692

INTRODUCTION

With principal support from the Office of Naval Research, a broad program in free-electron laser research is now being carried out at the University of California, Santa Barbara. The program contains two major components: 1) the development of free-electron laser radiation sources based on electrostatic accelerators and, 2) the utilization of these sources in scientific research.

The UCSB FEL operation is based on the utilization of a 6 MeV electrostatic accelerator which has been modified to generate high current electron pulses of sufficient intensity to drive FELs as oscillators over a wide range of frequencies from the infrared (IR) to the far-infrared (FIR) region. Furthermore, the UCSB FEL incorporates in its design a means to recover the unspent energy of the electron beam in order to increase laser power and efficiency and to decrease unwanted ionizing radiation.

The evolution of the UCSB FEL has proceeded through a series of technical phases which began with the development of a unique, high current, high optical quality electron gun in 1982, continued with the successful demonstration of very high electron beam recovery efficiency in 1983[1], and culminated with the operation of the FEL as an oscillator at a wavelength of 400 μm in 1984. In 1985 the accelerator voltage was upgraded from 3 MV to a maximum of 6 MV. Since then, the FEL has been running on a routine basis as a continuously tunable source of radiation for scientific research in the 120 to 800 μm FIR region. Also in 1985, the UCSB FEL first demonstrated single mode operation with very narrow spectral bandwidth[2]

Presently, a number of FEL concepts are being developed at UCSB. Included among these are: two-stage FELs[3], microundulator FELs[4], intermediate[5] size FELs for the FIR region and compact FELs for the mm and submillimeter region.

As part of the scientific application program a number of scientific experiments are currently being carried out at the UCSB FEL facility. For example, transmission studies of FeF_2 were initiated in 1985. In 1986 one experiment in non-linear properties of GaAs was completed, and one experiment designed to study the response of cells to high-power FIR radiation appears to show unexpected results.

The first part of this report deals with the developmental aspects of FELs at UCSB, while the second part summarizes results obtained in the scientific applications program.

FEL DEVELOPMENT PROGRAM

The existing, fully operating UCSB FEL is unique among all others in its use of the electrostatic accelerator which has proven to be an ideal source for an FEL. Among its advantages are:

- Excellent electron beam quality
- Excellent electron beam recovery
- High operating laser efficiency
- Very low Ionizing radiation
- Variable electron pulse structure
- Simple and reliable operation
- High spectral resolution

In this section an outline of the development aspects of the UCSB FEL program is presented. Included among these are: electron beam system, present FEL operation, two-stage FELs, microundulators, and compact FELs.

Electron beam system.

Electrostatic accelerators are routinely used as high quality sources of low current (i.e. a few μA), low voltage ($V <$ 25 MV) ion beams. However, as was demonstrated[1] by the UCSB FEL group in 1983, these devices can also generate long, ampere-level, electron beam pulses using electron beam recovery techniques.

Because of their limited charging current characteristics, typically only a few microamperes of useful beam current can be generated on a continuous basis by these machines. Through electron beam recovery, however, the amount of available beam current can be considerably increased. If I_b, I_c, C, and V are respectively electron beam current, accelerator charging current, accelerator electrical capacitance, and accelerator voltage, then the rate of change of beam voltage due to incomplete beam recovery is given by

$$\frac{dV}{dt} = \frac{I_b(1-R) - I_c}{C}, \qquad (1)$$

where R is the fraction of recovered electron beam. For $R \approx 1$ it is possible to operate the accelerator at constant voltage on a continuous basis. For $R < 1$ the accelerator must be operated on a pulsed mode basis with maximum beam duty cycle given by

$$D.C. = \frac{I_c}{I_b(1-R)}, \qquad (2)$$

where I_c is the net charging current available. In this mode of operation the electron beam voltage first decreases with time at the rate described by equation (1). After the electron beam pulse is turned off the accelerator is charged back to its initial voltage at a rate $-I_c/C$.

Two crucial technology demonstration experiments were first carried out by the UCSB FEL group before determining whether electrostatic accelerators could be considered as suitable drivers of FELs. Early in 1983 a beam recovery test, which was carried out with the help of National Electrostatic Corporation in Middleton, Wisconsin, demonstrated a beam recovery rate of 99.4%. With this experiment, long-pulse, ampere-level current generating capabilities of electrostatic accelerators were firmly established. Later, in 1983, a second test, which was designed to study the optical beam quality produced by a high-voltage electrostatic accelerator, yielded a normalized transverse emittance measurement (see Table I) which was not much different from that measured for the electron gun. As it turned out, the measured gun emittance[1] was nearly the same as the theoretical thermal value calculated for the gun cathode. This result confirmed that properly designed electrostatic accelerating fields do not increase appreciably the beam emittance and that the value of the emittance produced is much smaller than that required by typical FELs, including two-stage FELs.

Figure 1 shows the mechanical design of the first electron gun used with the UCSB FEL project. Its design philosophy was motivated by two critical needs. First, the electron beam quality had to be high in order to achieve high electron beam recovery rates and to simultaneously satisfy beam quality demands imposed by FELs in general and two-stage FELs in particular. The final gun design incorporated a gridless dispenser cathode from which electrons were extracted by means of a pulsed modulating anode, as shown in the figure. Second, the electron gun optics had to be properly matched to that of the accelerator tubes. Figure 2, illustrates the beam envelope evolution of a 2 ampere electron beam as it is accelerated through a properly matched 3 MV accelerator section.

The major components of the UCSB electrostatic accelerator are shown in Figure 4. The electron gun and collector are attached directly to accelerator and decelerator tubes. Figure 5 shows the four-stage, 10 KV electron collector presently used in conjunction with the decelerator tube as the last stage of electron beam recovery. The collector allows for efficient recovery of an electron beam containing the 10 keV energy spread component induced by the FEL interaction process. It is attached to the electron gun through D.C. power supplies, which replace the

energy converted by the electron beam into electromagnetic radiation. The HV supply consists of two pelletron chains capable of delivering up to 200 μA of charging current. All components are housed inside a steel tank containing electrical insulating gas (SF_6) held at 85 psi pressure.

Figure 5 illustrates the beam recovery apparatus fabricated in 1983 to test the high current generating capabilities of electrostatic accelerators. Results of these tests have been included in Table I.

Table I. Electron beam characteristics of the UCSB electrostatic accelerator.

Max. charging current	200	μA
Max. beam current		
E.Gun #1	2.6	A
Max. recovery rate	99.4	%
Transverse emittance		
(normalized)	$10^{-5}\pi$	mrad
Maximum voltage	6	MV
Maximum energy spread		
stochastic	0.2	eV
voltage droop	300	V/μs
Maximum duty cycle	1	%

FEL Operation.

A schematic diagram of the UCSB FEL apparatus is shown in Figure 6. Included are the 6 MV electrostatic accelerator, a number of electron beam optical components which allow transporting, and matching the electron beam in and out of the FEL interaction region, a permanent magnet undulator and the hybrid mode resonator.

The UCSB FEL utilizes a cylindrical wave resonator[6]. It is constructed from two parallel stainless-steel plates having two cylindrical copper mirrors located between them in a nearly confocal arrangement. The fundamental cavity mode consists of a cylindrical standing wave which is guided in one direction by the metal plates and is free in the direction parallel to the plates. The output coupling is accomplished by inserting a small diameter (3mm) copper mirror inside the cavity at an angle of 45^{o} with respect to the axis of the resonator.

Table II summarizes the UCSB FEL resonator/undulator design parameters.

Table II. UCSB FEL resonator and undulator design parameters.

Undulator (samarium-cobalt)		
geometry		Halbach
period		3.6 cm
gap	3.8	cm
on-axis-field	700	gauss
Waveguide resonator (stainless steel)		
height	1.9	cm
width	13.4	cm
length	715	cm
Mirrors (copper)		
geometry		cylindrical
height	1.85	cm
width	10	cm
curvature	500	cm
Fundamental mode parameters		
mode structure	cylindrical waves	
wavelength	400	μm
hor. beam waist	1.14	cm
mirror losses	0.3	% each
output coupler	11	%
waveguide losses	1	%

The UCSB FEL has been in operation since 1984. It is operated on a daily basis for periods as long as 16 hours. A typical time between failures is 4 months. Some of its operating characteristics have been included in Table III.

Table III. Operating characteristics of the UCSB FEL.

Peak power	10-40	kW
Wavelength	120-800	μm
Fractional frequency bandwidth		
single pulse	10^{-8}	
pulse/pulse	10^{-3}	
Max. pulse length	0.5-50	μs
Rep. rate	1	Hz
Number of modes	1	

Typical oscilloscope traces describing the time structure[2] of the UCSB FEL are shown in Figures 7 and 8. The signal was obtained with a fast Schottky-diode detector. This is a square law detector showing the rf modulation resulting from the beating between two or three longitudinal cavity modes. The pulse envelope represents the power contained in a dominant single cavity mode. The "noise" riding on top of the pulse represents the beating of the dominant single cavity mode with adjacent longitudinal modes. Figure 8 shows an amplified view of a portion of the pulse shown in Figure 7. The power carried by adjacent longitudinal modes is less than 1% of that carried by the dominant mode. From the pulse length it has been estimated that the bandwidth of the laser is about 30 kHz.

Two-stage FELs.

The idea behind two-stage devices is to generate short wavelength radiation utilizing relatively low-voltage electron beams, such as the ones available at UCSB. The first proposal for a two-stage free-electron laser[3] dates back to 1979.

Two such devices are under construction at UCSB. The first device utilizes one electron beam to generate the two FEL interactions. Figure 9 illustrates the UCSB electron beamline design including the section associated with the two stage FEL (i.e. the numbered components). Figure 10 shows the details of the resonator while Table IV summarizes the design for this device.

Table IV. The UCSB Two-stage FEL beamline.

Stage	1st	2d
Energy(MeV)	6	6
Current(amps)	20	20
Wavelength(μm)	703	1
# of periods	14	4000
Small signal gain(%)	12	10
Peak power(kW)	2000	15

A second device is being developed on a collaborative basis with Hughes Research Laboratory. It utilizes two separate electron beams to achieve the same goal as the single beam device discussed above.

Microundulators.

Conventional undulators, such as the Halbach configuration (see Fig. 11a), used in the present UCSB FEL, consist of individual magnets with dipole moment successively rotated by $\pi/2$. Recognition of the difficulty of handling individual magnets of the dimensions required for a short period undulator motivated the development of alternate configurations referred to as "microundulators". These structures consist of grooves ground in large blocks of material, as shown in figures 11b and 11c. Periods as short as 1 mm using blocks of approximately 5x5 cm appear practical. The field orientation of the blocks (Fig. 11b) forces flux return paths to exist around the edges and ends, resulting in deleterious transverse quadrupole fields and axial end fields. The configuration in Fig. 11c not only avoids the quadrupole fields but its end fields can be shaped to provide electron beam injection dipoles. Neodymium-iron-boron blocks ground to the

configuration (Fig. 11b) are now being tested for magnetic field homogeneity.

Micro-undulator FELs have a number of significant advantages resulting from a combination of effects. The short period and consequent small resonator size, permit resonator placement within the accelerator terminal. This results in a simple direct electron beam optical system as shown in Fig.12. The UCSB FEL group is presently studying the possibility of mechanically integrating the undulating magnets with the electromagnetic resonator. That is to say, the grooves of the microundulators would become distributed feedback (Bragg) reflectors. This idea will become more important when applied to microundulators used in the optical klystron configuration.

The microundulator concept provides a clear evolutionary path in the development of FEL technology that promises compact and efficient FELs for the submillimeter region and near infrared to visible operation with the higher voltage electrostatic machines.

Compact FELs.

An alternative to the UCSB FEL configuration is one in which the accelerator used is a positively charged machine with the electron gun and electron collector located at ground potential and an FEL interaction region placed inside the high voltage terminal. A schematic diagram of a 2 MV FIR FEL, configured with a positive high-voltage terminal, is shown in Figure 12. The electron beam, generated by a thermionic electron gun located at ground potential, is accelerated toward the positive terminal where a part of its energy is converted into laser radiation. The electron beam is then decelerated and eventually captured by the electron collector which is electrically connencted to ground potential through a DC power supply. This supply replaces the amount of energy lost by the electron beam to laser radiation.

There are a number of benefits derived from positively charged electrostatic accelerator FELs. For example, the shorter path and smaller number of beam optical components needed to transport the electron beam mean less aberration and degradation of emittance as well as smaller current loss. This should permit recirculation values greater than 99%. Thus laser efficiency would increase with corresponding decrease in unwanted ionizing radiation.

SCIENCE APPLICATIONS PROGRAM

Notwithstanding the abundance of sources which are presently available, significant portions of the electromagnetic spectrum, from microwaves to the X-ray region, are devoid of intense sources for research. The potential use of free-electron lasers to fill these voids has been recognized by a National Academy of Science study. It has concluded that there exist significant opportunities for scientific research using FELs operating at wavelengths shorter than 200 nm or greater than 25 μm. The far-infrared (FIR) is one region where conventional sources are notoriously weak except at a set of discrete frequencies where molecular lasers operate. The advent of the UCSB FEL has changed this situation dramatically. With its combination of high power, continuous wavelength tunability, and high spectral resolution, it is now opening many areas of scientific research in the FIR region. Of particular interest to condensed matter physicists is the spectroscopic study of the numerous low energy excitations (e.g. magnons, phonons, polaritons, plasmons, etc.) which occur in solids in this region.

From the onset, a prime objective of the University of California, Santa Barbara Free-Electron Laser program was the ultimate utilization of the intense, tunable, FIR photon source for scientific applications. Initial realization of this goal began to take place in early 1986 with preliminary investigations of specific solid state problems. The first experiments were chosen to test the ease with which the FEL could be tuned, its

short term amplitude and frequency stability, and to develop procedures necessary to execute more sophisticated studies.

The first study made was that of the magnetic polariton in antiferromagnetic FeF_2. The observed transmission spectrum is shown in Figure 11 along with computer simulation of it using the known exchange and anisotropy parameters of FeF_2.

The most interesting experiments will be in nonlinear and non-equilibrium studies in the FIR. An indication of the broad range of possible applications of the FEL to problems in the various sciences that have been proposed by current users and users-to-be include:

- Biomedicine

Cellular studies including the search for "windows" in the FIR; inactivation, selective destruction and generation of nonlinear processes in cells; animal studies to determine effectiveness of intense FIR on tumors.

- Biophysics

Athermal melting of DNA using intense resonance excitation; nonlinear response of DNA in two-photon, one "phonon" experiments.

- Solid State Physics

Nonlinear excitation of phonons and magnons of arbitrary wave vector; propagation and lifetime studies of same; dynamics of localized modes; nonlinear excitations in semiconductor superlattices; nonequilibrium processes in superconductors.

- Surface Science.

Alteration of reaction rates through selective nonlinear excitations; preparation of new materials through selective decomposition; lifetime studies of impurity ions in zeolite.

Within the UCSB Quantum Institute the Center For Free-Electron Laser Studies (CFELS) has been created to enhance the direct interaction between those involved in new concepts in FEL design and the scientists whose needs will be met by current and future advances in FEL development.

The author wishes to acknowledge the collaboration from V. Jaccarino, G. Ramian, I. Kimel, J. Gallardo, J. Hu, A. Avner, P. Burris, and the rest of the UCSB FEL technical staff.

REFERENCES

[1] L.R. Elias and G.J. Ramian, Free Electron Generators of Coherent Radiation, eds., C.A. Brau, S.F. Jacobs and M.O. Scully, SPIE 453 (1983) 137-144.

[2] L.R. Elias et. al., Phys. Rev. Lett. **57**, 424-427(1986).

[3] L.R. Elias, Phys. Rev. Lett. **42**, 977(1979); and in:Free electron Lasers, eds. S. Martellucci and A.N Chester (Plenum, New York, 1979) p617-631.

[4] G. Ramian et al.,Nuc. Inst. and Meth. A250(1986) 125-133.

[5] G. Ramian et al.,"Evolutionary paths in electrostatic accelerator FEL development", to be published in Nuclear Instruments and Methods-part A(1987).

FIGURE CAPTIONS

Figure 1. Mechanical design of electron gun #1.

Figure 2. Beam envelope evolution of a 2 ampere beam inside a 3 MV accelerator.

Figure 3. Four-stage, 10 kV electron collector.

Figure 4. The UCSB electrostatic accelerator.

Figure 5. Beam recovery apparatus.

Figure 6. Schematic diagram of the UCSB FEL apparatus.

Figure 7. Time structure a UCSB FEL pulse. The envelope represents the power in a single mode.

Figure 8. Amplified time structure of the top of the pulse shown in Figure 7. It is associated with the beating of a dominant laser longitudinal mode with one or two adjacent longitudinal modes.

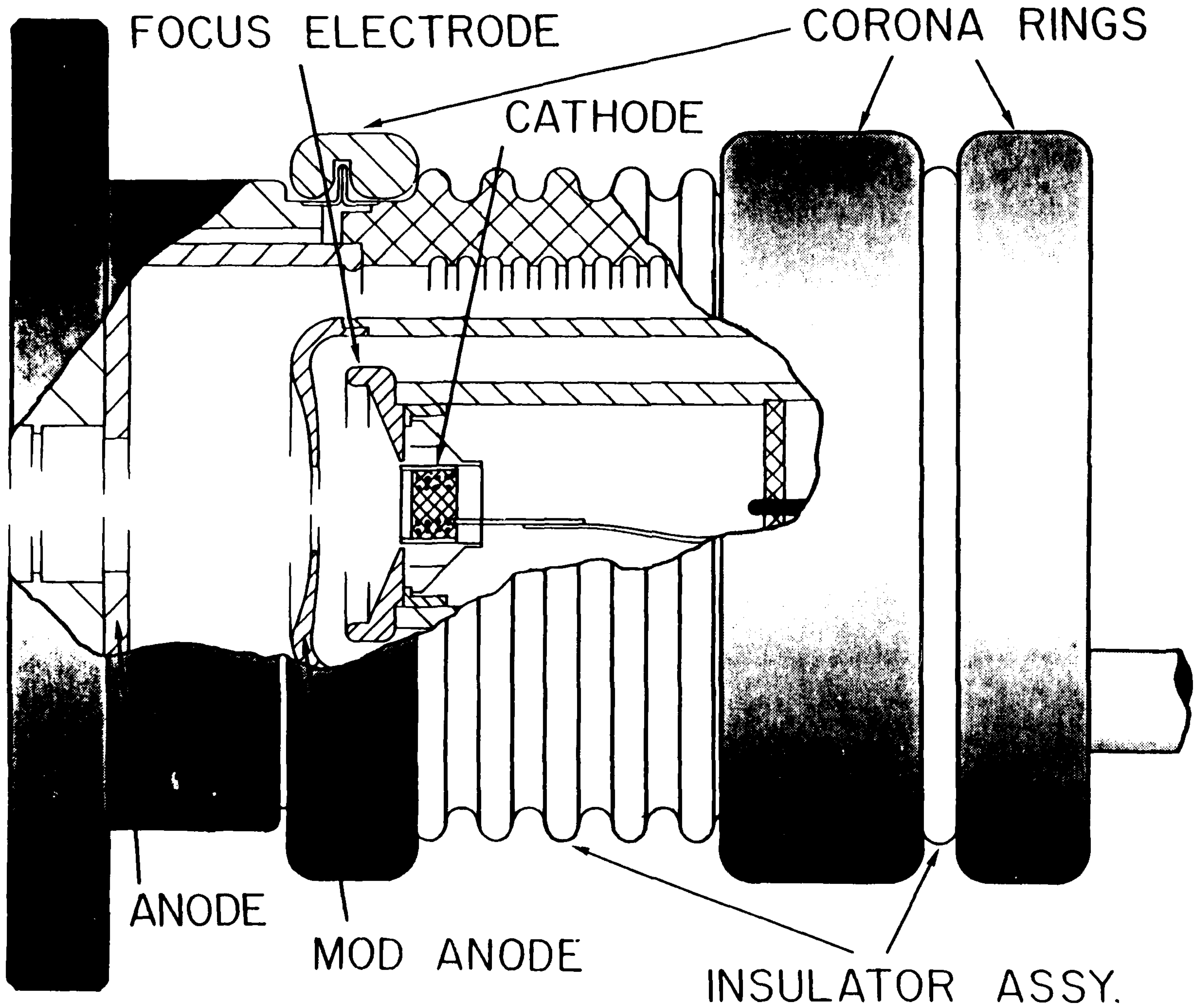
Figure 9. UCSB beamline design. The numbered components are part of the two-stage beamline.

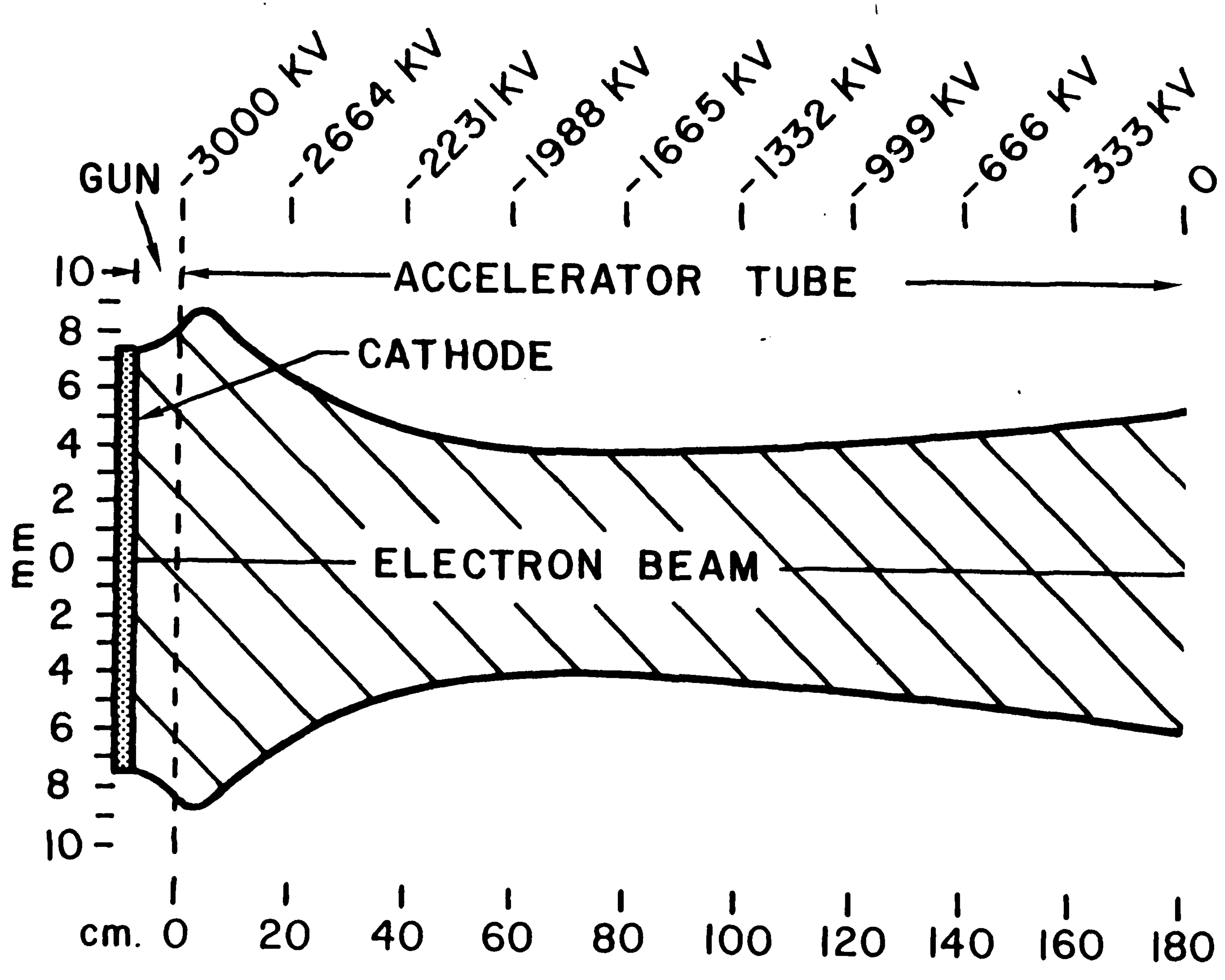
Figure 10. The UCSB two-stage resonator.

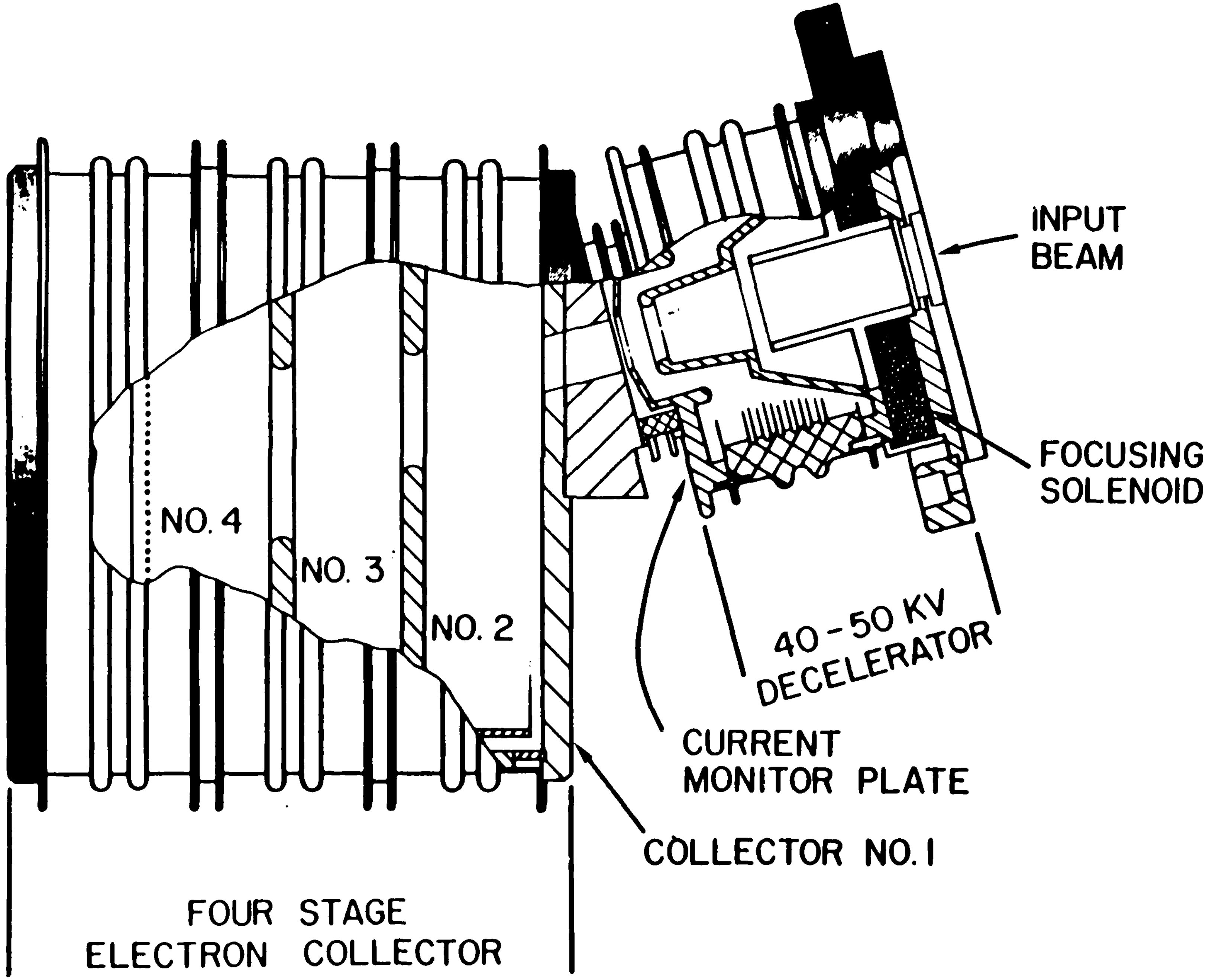
Figure 11. Halbach undulator (a) and microundulators (b and c).

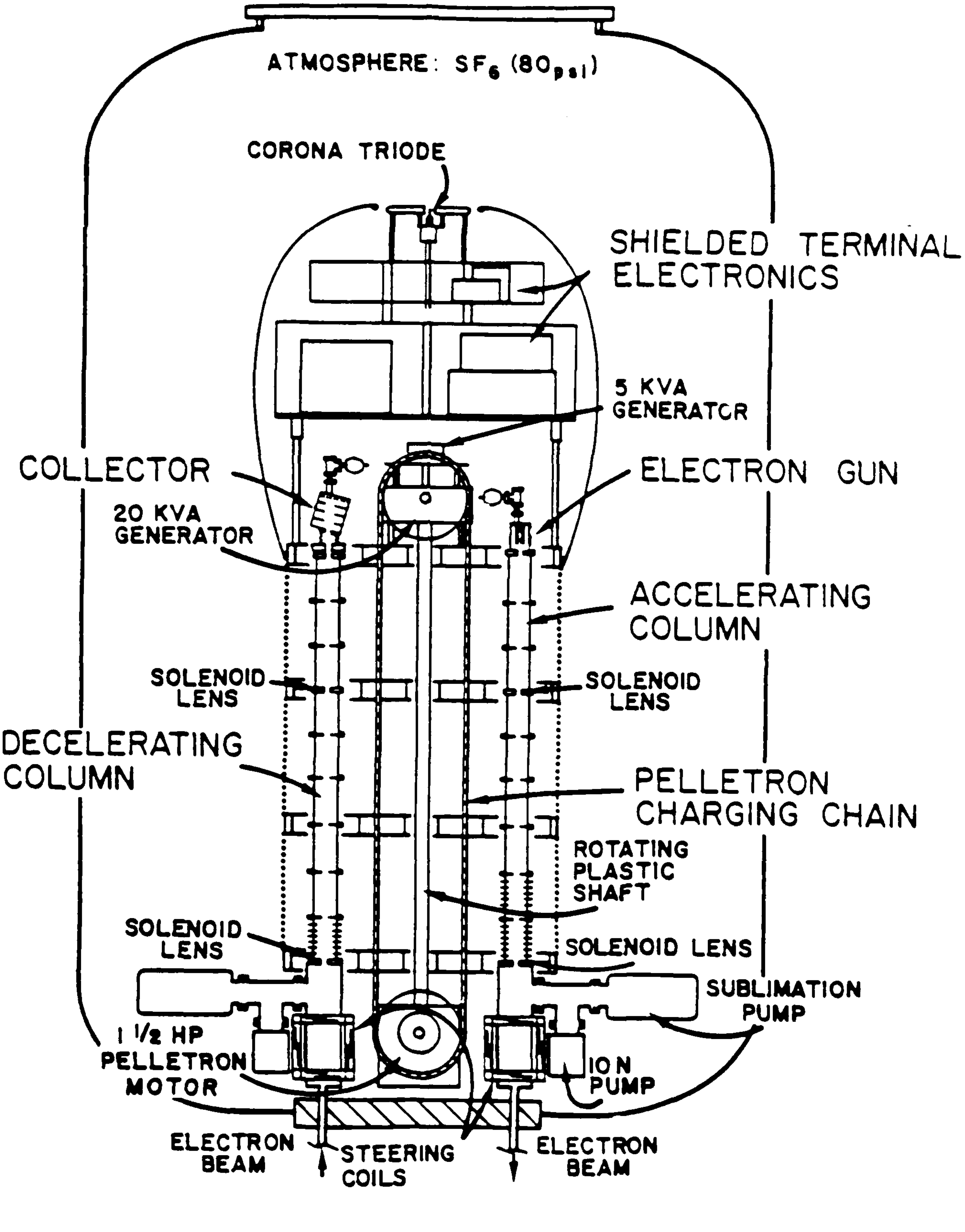
Figure 12. A compact 2 MV FEL using a posively charge electrostatic accelerator.

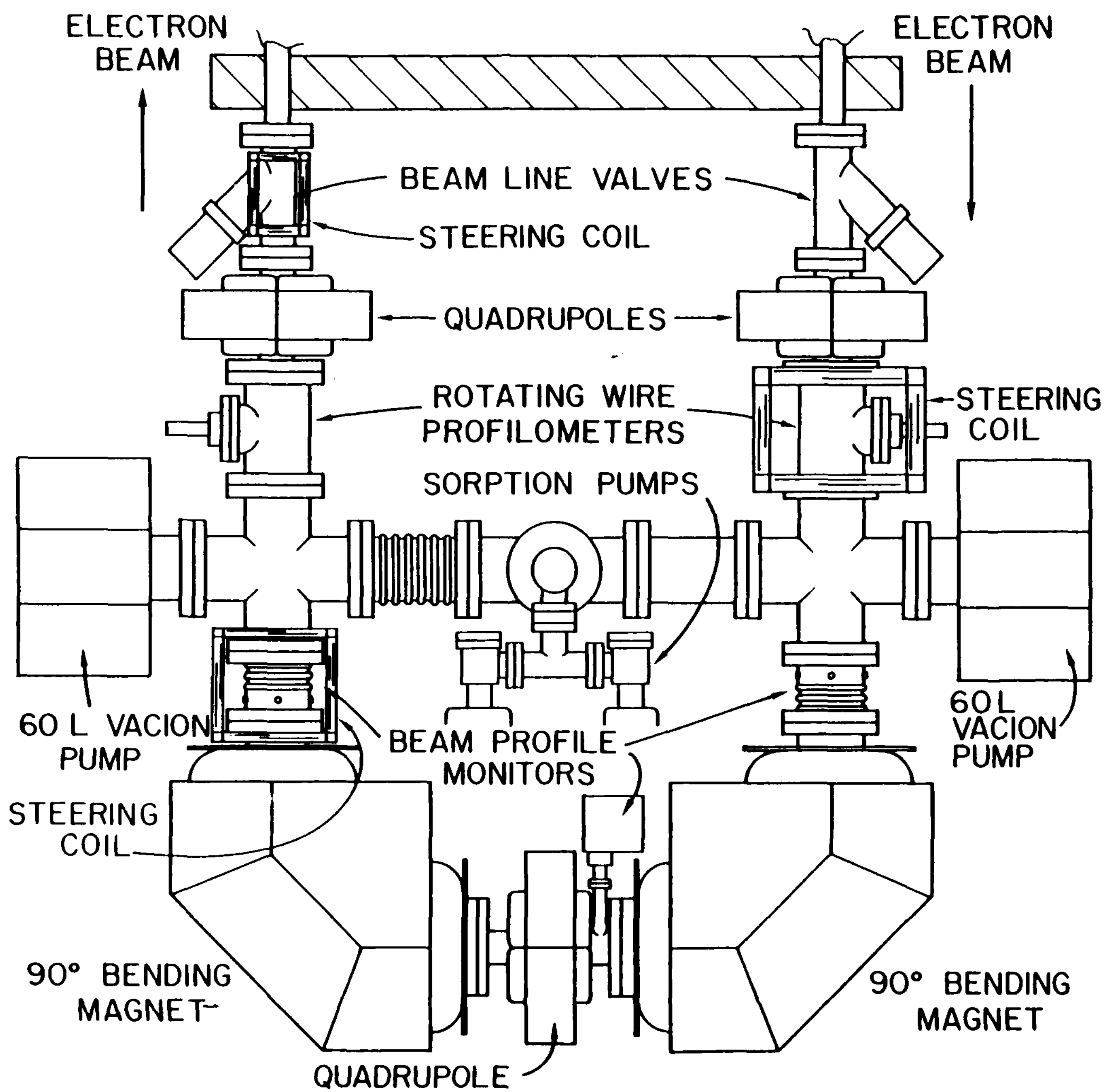
Figure 13. Transmission spectrum of antiferromagnetic FeF_2.


FOCUS ELECTRODE
CORONA RINGS
CATHODE
ANODE
MOD ANODE
INSULATOR ASSY.

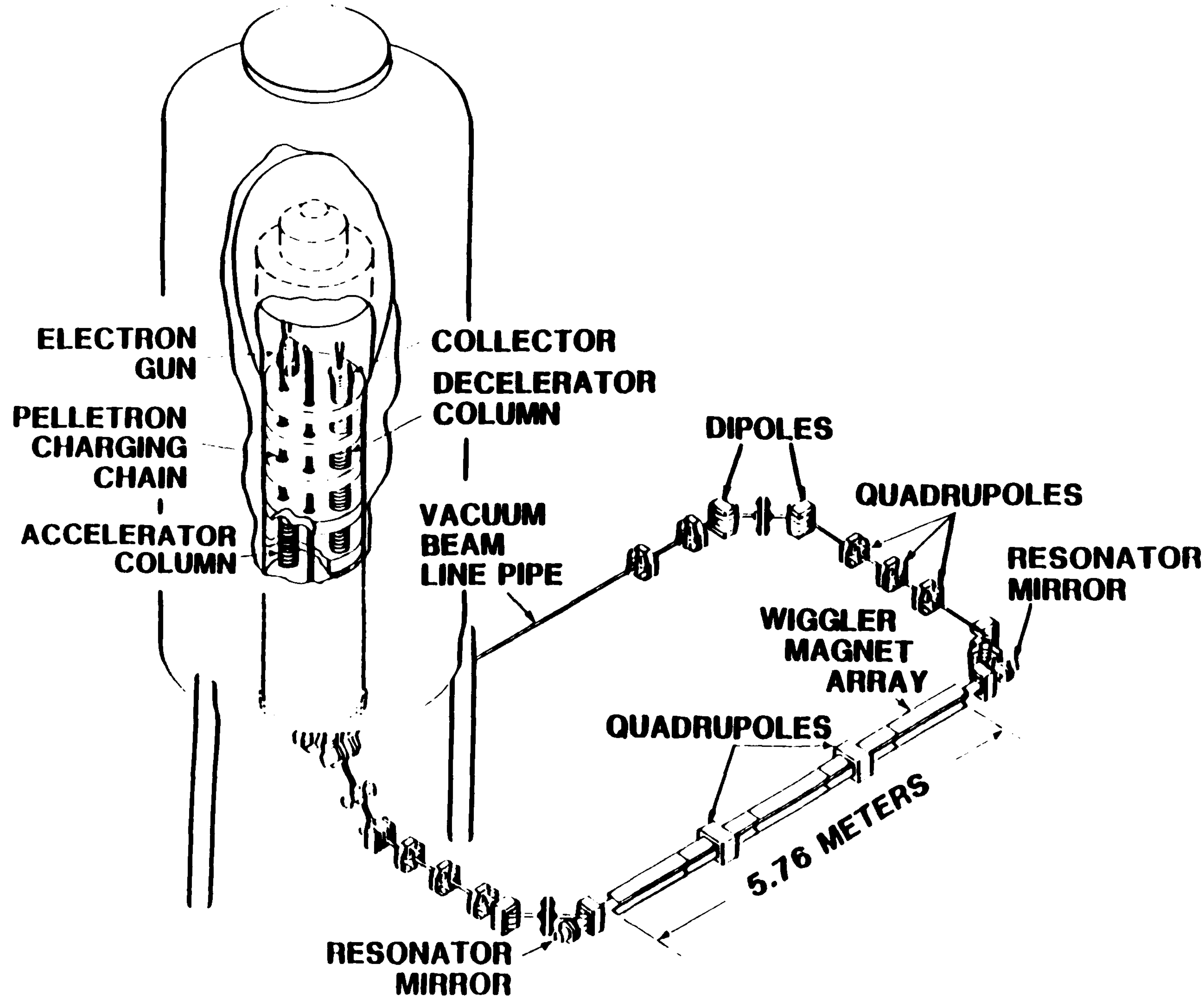

GUN
-3000 KV
-2664 KV
-2231 KV
-1988 KV
-1665 KV
-1332 KV
-999 KV
-666 KV
-333 KV
0
ACCELERATOR TUBE
CATHODE
ELECTRON BEAM
mm
10
8
6
4
2
0
2
4
6
8
10
cm. 0
20
40
60
80
100
120
140
160
180

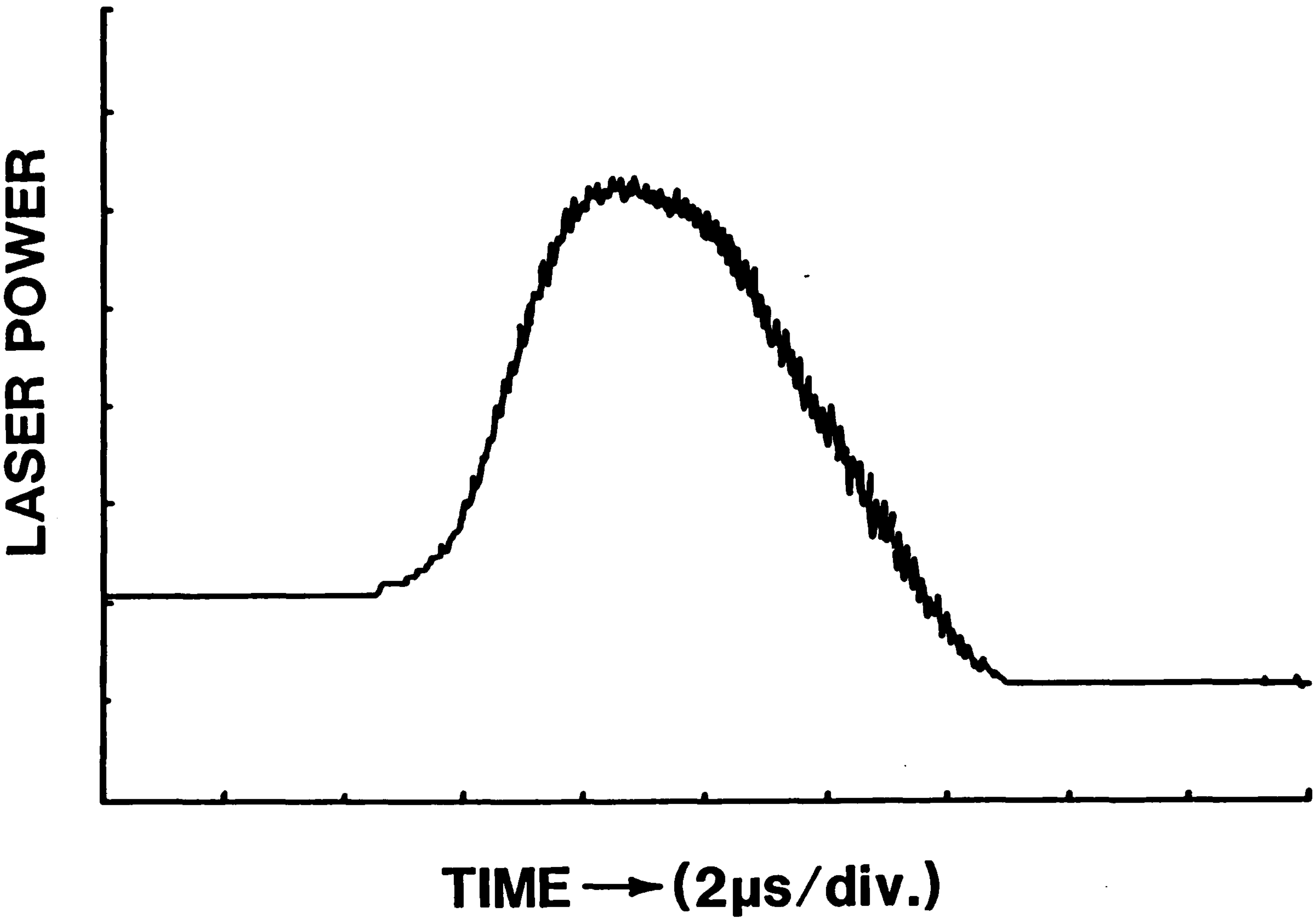

INPUT
BEAM
FOCUSING
SOLENOID
40 - 50 KV
DECELERATOR
CURRENT
MONITOR PLATE
COLLECTOR NO. 1
NO. 2
NO. 3
NO. 4
FOUR STAGE
ELECTRON COLLECTOR

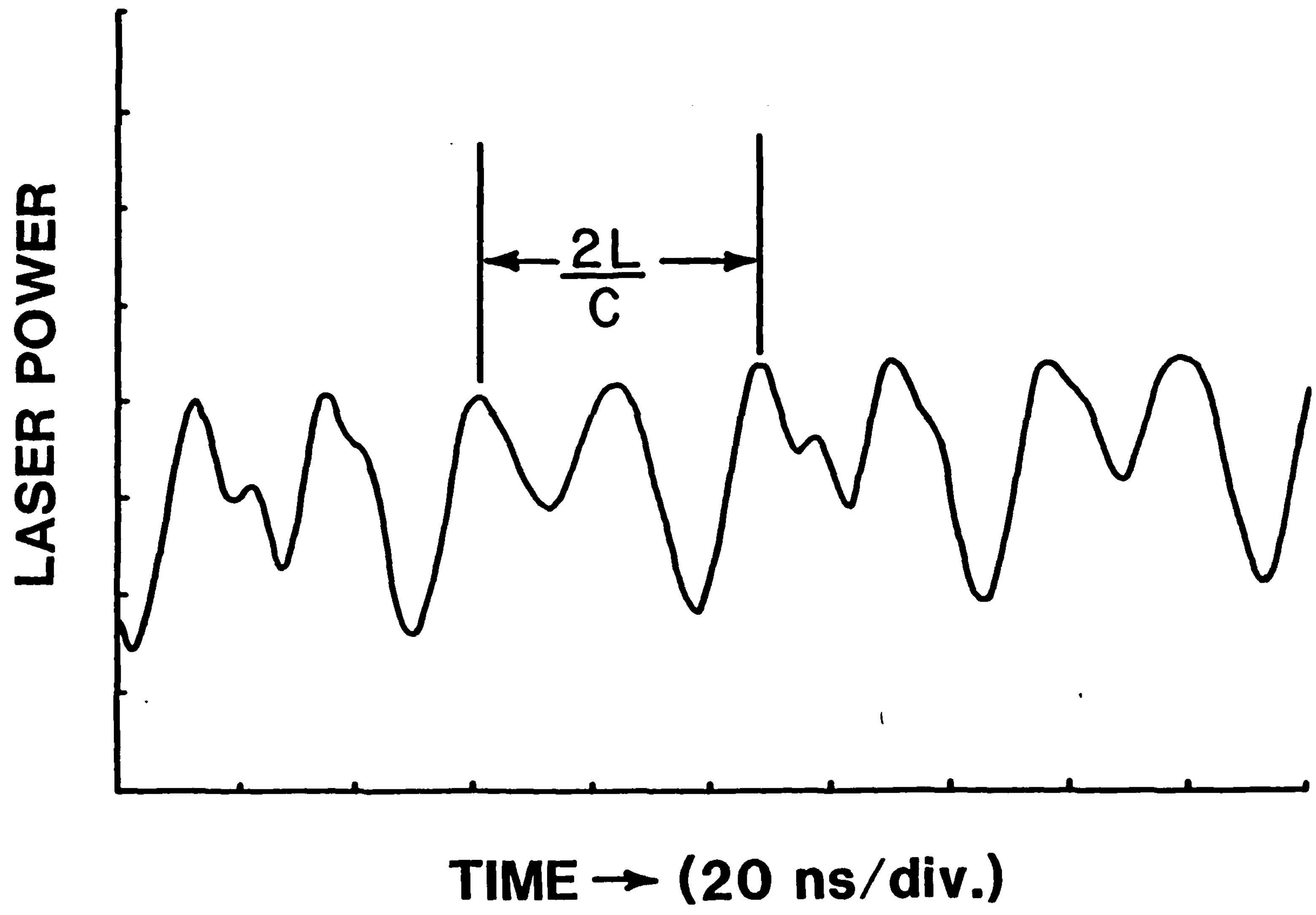

ATMOSPHERE: SF6 (80psi)
CORONA TRIODE
SHIELDED TERMINAL ELECTRONICS
5 KVA GENERATOR
COLLECTOR
ELECTRON GUN
20 KVA GENERATOR
ACCELERATING COLUMN
SOLENOID LENS
SOLENOID LENS
DECELERATING COLUMN
PELLETRON CHARGING CHAIN
ROTATING PLASTIC SHAFT
SOLENOID LENS
SOLENOID LENS
SUBLIMATION PUMP
1 1/2 HP PELLETRON MOTOR
ION PUMP
ELECTRON BEAM
STEERING COILS
ELECTRON BEAM

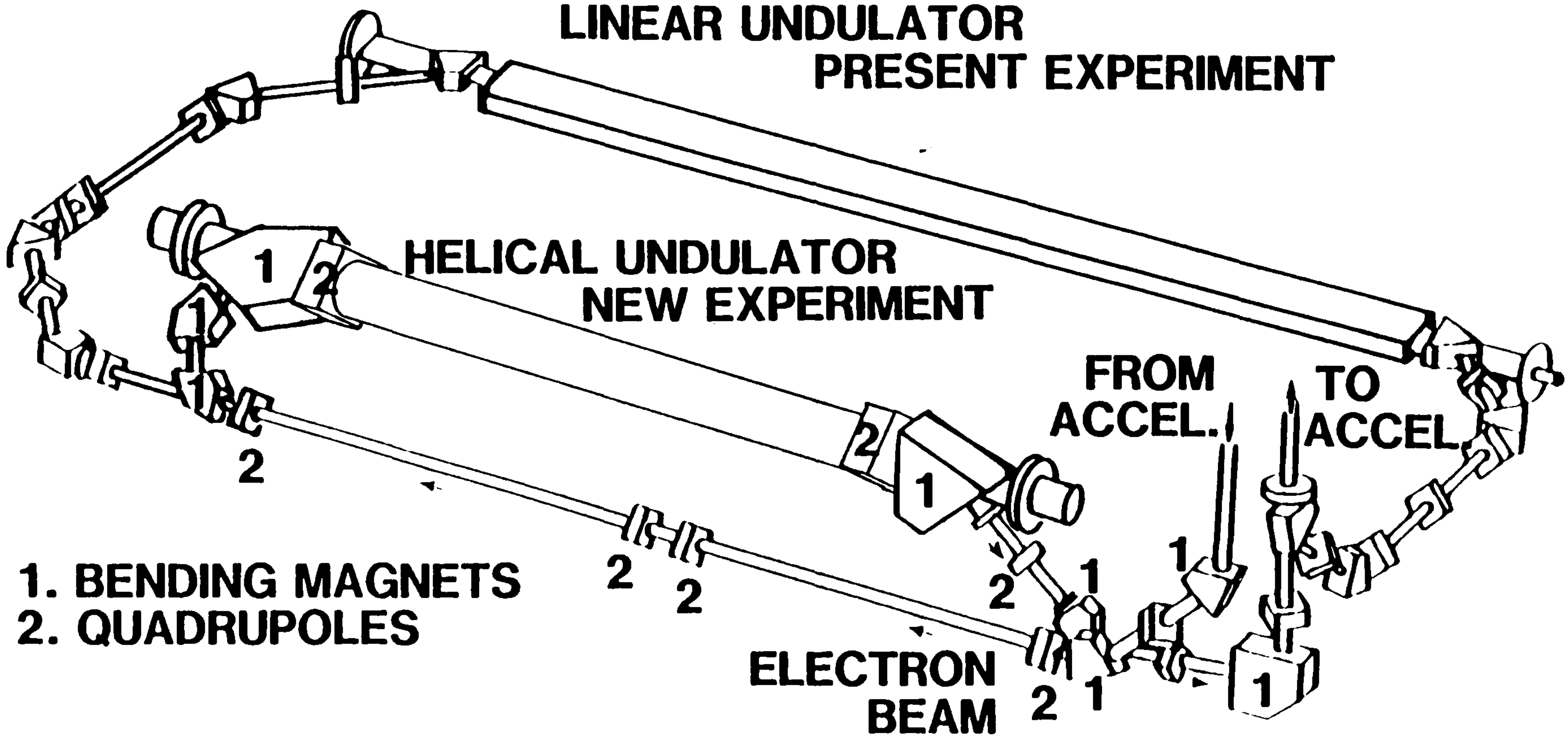


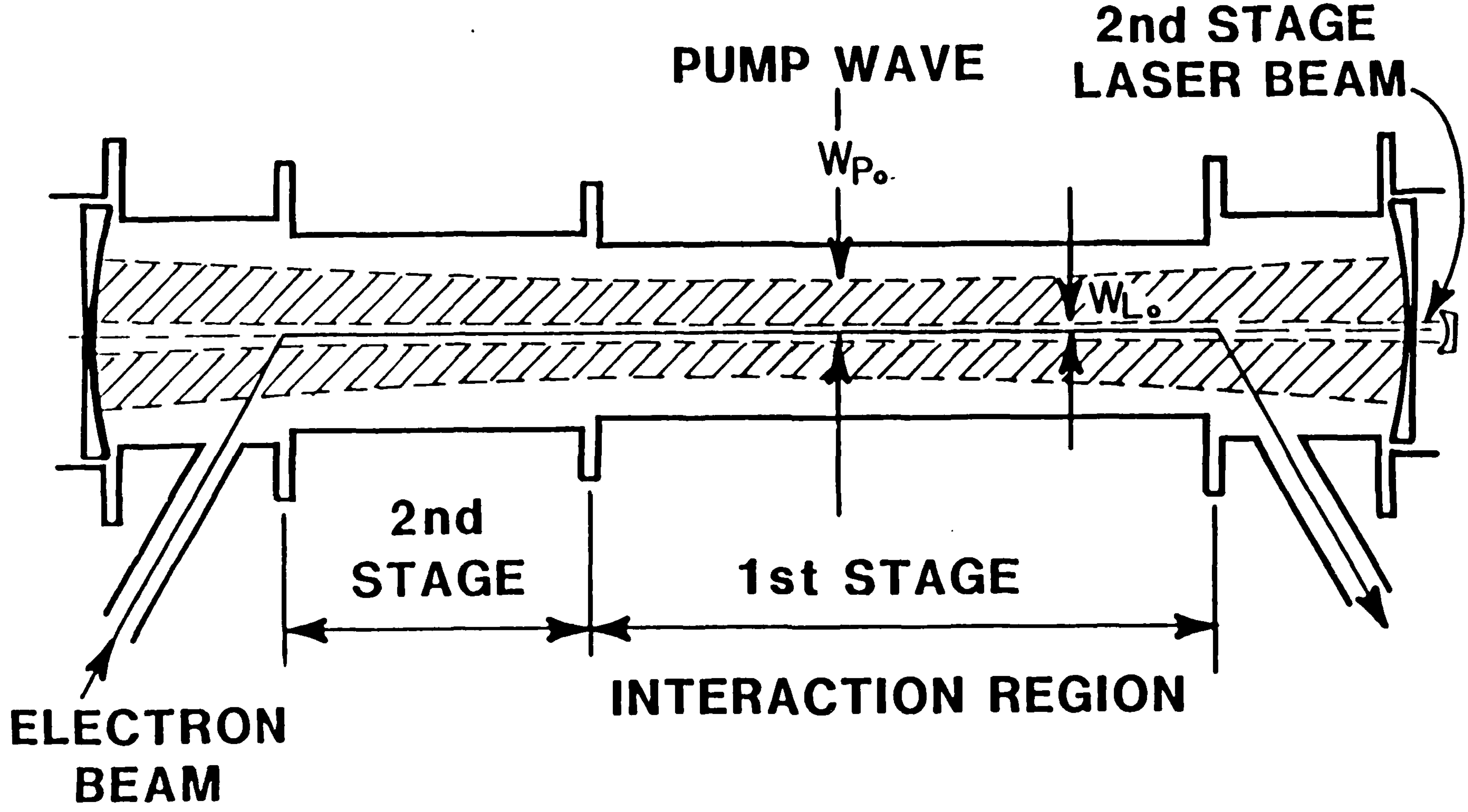
ELECTRON
BEAM
ELECTRON
BEAM
BEAM LINE VALVES
STEERING COIL
QUADRUPOLES
ROTATING WIRE
PROFILOMETERS
STEERING
COIL
SORPTION PUMPS
60 L VACION
PUMP
60 L
VACION
PUMP
BEAM PROFILE
MONITORS
STEERING
COIL
90° BENDING
MAGNET
90° BENDING
MAGNET
QUADRUPOLE

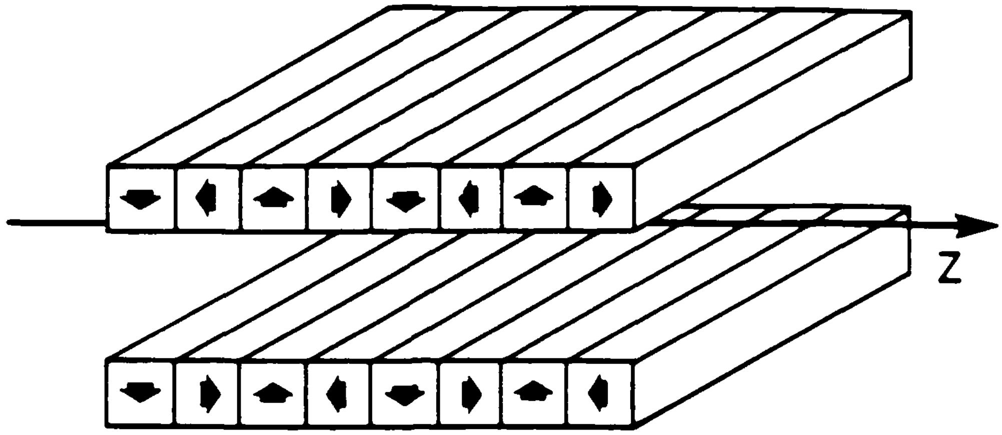

ELECTRON GUN
PELLETRON CHARGING CHAIN
ACCELERATOR COLUMN
COLLECTOR
DECELERATOR COLUMN
VACUUM BEAM LINE PIPE
DIPOLES
QUADRUPOLES
RESONATOR MIRROR
WIGGLER MAGNET ARRAY
QUADRUPOLES
5.76 METERS
RESONATOR MIRROR


LASER POWER
TIME → (2μs/div.)

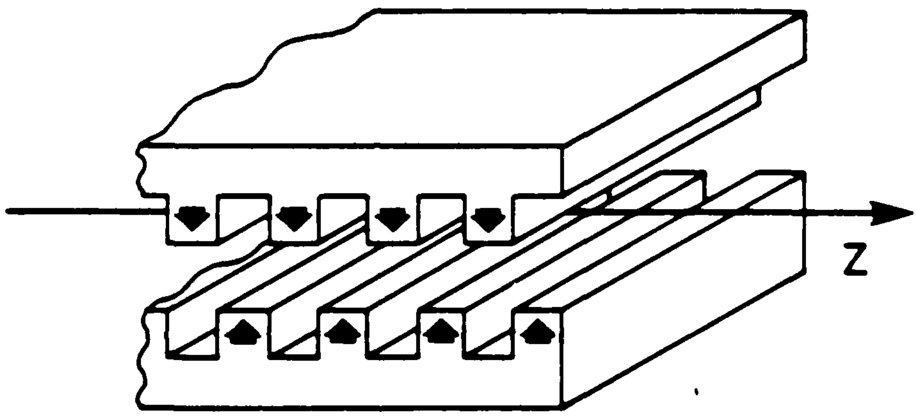

LASER POWER
2L/C
TIME → (20 ns/div.)


LINEAR UNDULATOR
PRESENT EXPERIMENT
HELICAL UNDULATOR
NEW EXPERIMENT
FROM
ACCEL.
TO
ACCEL.
ELECTRON
BEAM
1. BENDING MAGNETS
2. QUADRUPOLES

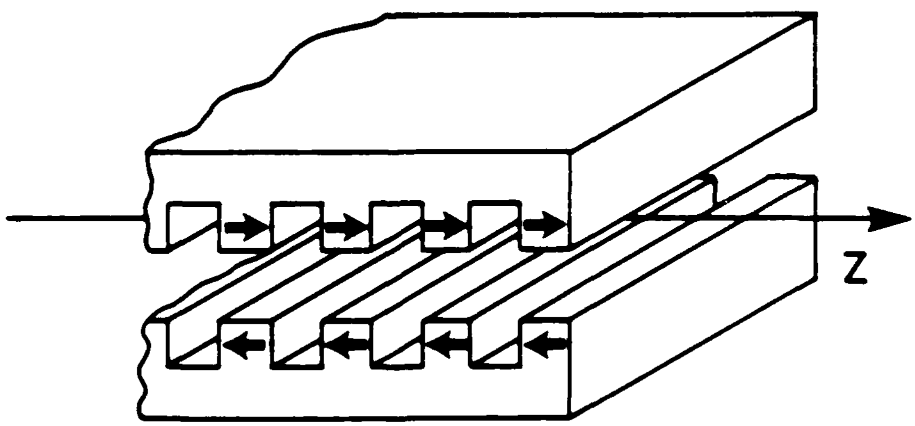

PUMP WAVE
2nd STAGE
LASER BEAM
W_{P_0}
W_{L_0}
2nd
STAGE
1st STAGE
INTERACTION REGION
ELECTRON
BEAM



a. HALBACH CONFIGURATION

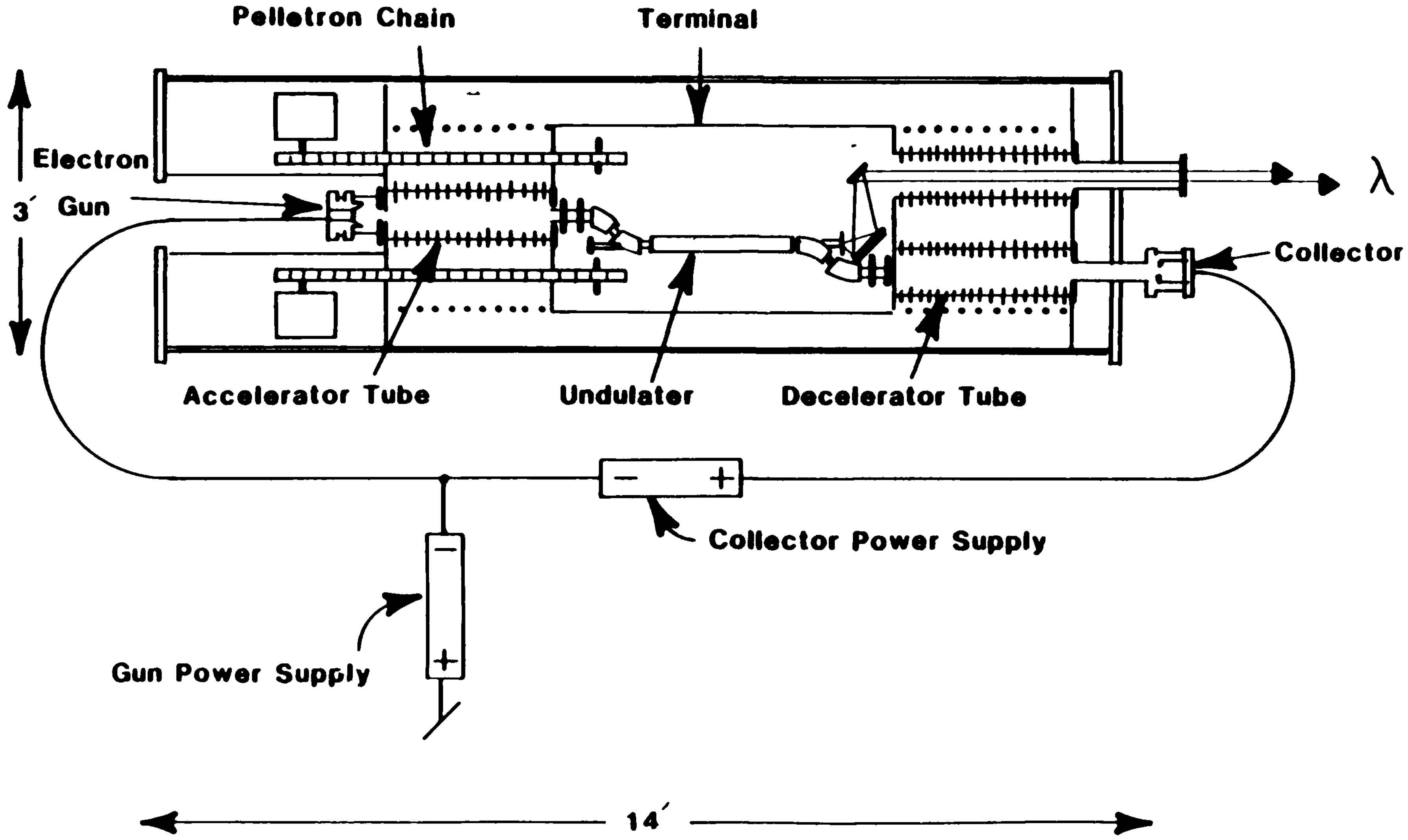


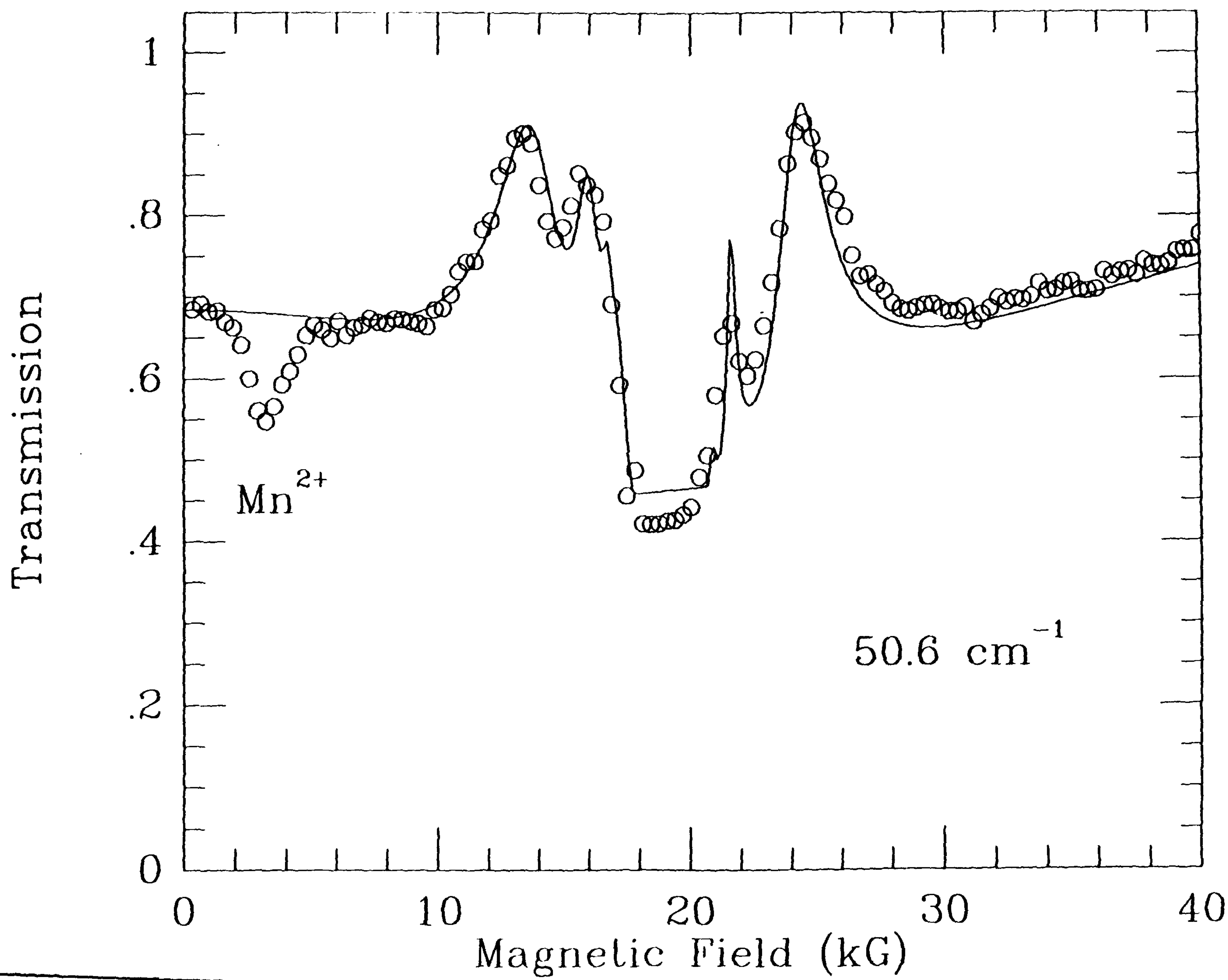
b. MICRO-WIGGLER #1



c. MICRO-WIGGLER #2

1 MEV FEL


Pelletron Chain
Terminal
Electron
Gun
3´
λ
Collector
Accelerator Tube
Undulater
Decelerator Tube
Collector Power Supply
Gun Power Supply
14´



Transmission
1
.8
.6
.4
.2
0
0
10
20
30
40
Magnetic Field (kG)
Mn^{2+}
50.6 cm^{-1}

END

9-87

DTIC